QUANTUM INTERFEROMETRIC LITHOGRAPHY: EXPLOITING ENGANGLEMENT TO BEAT THE DIFFRACTION LIMIT

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Abstract: Using photon number states entangled N at a time, it is possible to write features in an N-photon absorbing substrate that are a factor of N times smaller than allowed by the classical diffraction limit.

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Summary

It has been known for some time that entangled photon pairs, such as generated by spontaneous parametric down conversion [1], have unusual imaging characteristics with sub-shot-noise interferometric phase measurement [2,3]. In fact, Fonseca, *et al.,* recently demonstrated resolution of a two-slit diffraction patterned at half the Rayleigh limit in a coincidence counting experiment [3]. What we show is that this type of effect is possible not only in coincidence counting experiments, but also in real two-photon absorbing systems, such as those used in classical interferometric lithography. In particular, we will demonstrate that quantum entanglement is the resource that allows sub-diffraction limited lithography.

Consider the schematic set up for interferometric lithography, illustrated in the figure. We consider a two-port device with photons incident on a symmetric, lossless, beam splitter from the left in one or both ports. The photons are then reflected by a mirror pair onto the imaging plane of the substrate at the right. Without loss of generality, we can model the phase differential due to path length differences between the upper and lower branches of the interferometer as a single phase shifter placed in the upper branch, which imparts a phase shift φ=2kx, at grazing incidence. The photon paths converge on the imaging plane, as show in the figure.

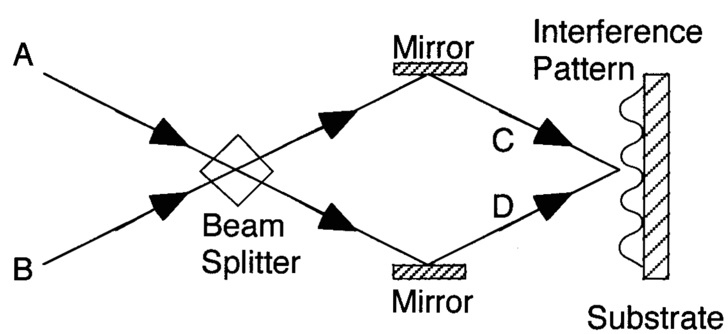

Fig. Typical Quantum Interferometric Lithography set up. Correlated photons enter into both input ports A and B and then exit from ports C and D to be directed onto an N-photon absorbing lithographic substrate.

We identify with the two input ports A and B at the left, a pair of photon annihilation operators [2]. We can take the output electric field operator at the image plane on the right to be proportional to the sum of two output operators from the upper and lower branches of the interferometer. Then the linear relationship between the two inputs and the two outputs allows us to compute output operators in terms of inputs. The total electric field operator at the substrate is then the sum of these. The two-photon absorption rate at the imaging surface will be proportional to the expectation values of the usual two-photon absorption operator. A simple choice of a highly nonclassical number-product state that accomplishes this is the two-photon state $|1\rangle_A|1\rangle_B$, which is the natural output of parametric downconversion [1]. This state becomes entangled in number and path upon passage through the beam splitter, which leads to a two-photon deposition rate of $1+\cos 2\varphi$ which should be compared to the "classical" uncorellated two-photon rate of, $(1+\cos\varphi)^2=3/2+2\cos\varphi+1/2\cos 2\varphi$ [5]. The entanglement in photon number and path has been used to selectively delete the slowly oscillating $\cos\varphi$ term by destructive interference, leaving a pattern with the promised resolution $x_{min}=\lambda/8$. This is a factor of two improvement over classical limit of $x_{min}=\lambda/4$. In general, entangled N-photon states can be used to write features with a resolution of $x_{min}=\lambda/(4N)$ in an N-photon absorbing substrate, surpassing the classical limit by a factor of 4N.

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